ELECTROSTATICS

I. ELECTRIC CHARGE

A. Charges at rest

1. Electrification--process that produces electric charge is confined to the object and not moving L electrostatic charge
2. static electricity--stationary electricity in the form of an electric charge at rest L friction

B. Two Kinds of Charge

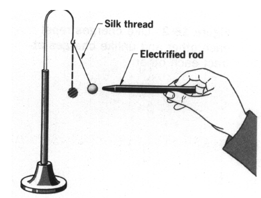
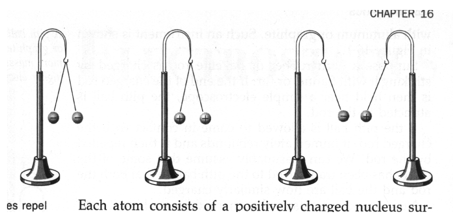


Figure 16-1. The pith-ball electroscope can be used to detect an electrostatic charge.

1. electroscope--detects electrostatic charges
   a. rubber/fur L repels
   b. glass/ silk L attracts
   c. therefore L 2 kinds of charge
2. Basic law of electrostatics--opposites attract and likes repel



C. Electricity and Matter

1. p+, e- and n^o # p+ = # e- so **NO** net charge on an atom

   a. e- mass = 9.1095 x 10^{-31} kg p+ mass = 1.6726 x 10^{-27} kg n^o mass = 1.6750 x 10^{-27} kg
   b. p+ & n^o bound in nucleus by strong forces acting through short distances
   c. repulsion between p+'s are due to weak forces
   d. e- hang around due to + attraction by nucleus; outer e-'s are held **less** strongly L especially metallic e-'s
   e. Two materials in close contact, some loosely held e-'s can be transferred from one material to the other

D. Electroscope

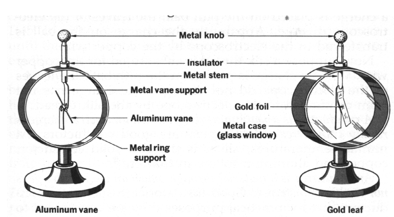


Figure 16-3. Two types of sensitive electroscopes.

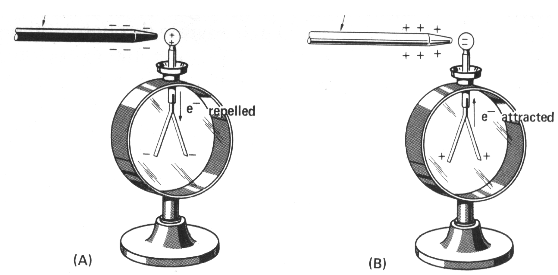
1. Vane electroscope--light Al rod mounted by central bearing on a metal support L vane is deflected and the angle depends on charge

2. Leaf electroscope--very fragile strips of gold leaf suspended from a metal stem
3. <u>proof plane</u>--test or transfer charges. Small metal disk with insulating handle

E. Conductors & Insulators (solids)
1. conductor--material that transfers Electric (e-) charge L Ag, Cu, Al
2. insulator--material that doesn't transfer e- charge L glass, mica, paraffin, hard rubber, sulfur, silk, **dry** air, plastic
3. Al--27g = 6.02 x 10^{23} atoms w/ 13 e- each = 7.83 x 10^{24} e- so 1e-/2.2 amu of matter
   a. metals have close packed crystal structures: + charged particles w/ a cloud of free e-'s L e- in a gas have same charge, repel and spread out. When they contact a charged body, e- surge
      + ½ e- or -¼ e-
      attracted repelled
4. Insulators lack free e- (usually not crystals either)

F. Transferring Electric Charges

Figure 16-6. An electroscope may be charged temporarily by induction because of a redistribution of the free electrons of the metallic conductor.



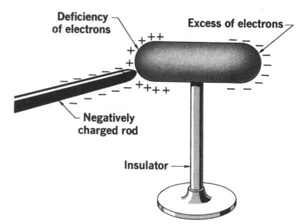
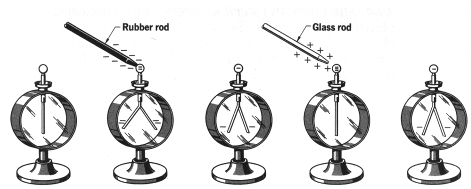
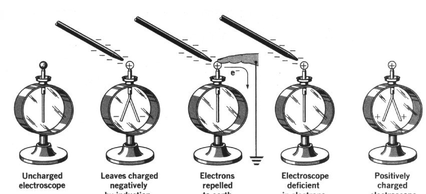


Figure 16-7. A charged rod brought near an isolated conductor induces electric charge of the same sign on the far end of the conductor.

1. e- travel from rod & cause leaves to diverge (repel) L induced charge
2. once source is removed free e- scatter throughout metal knob etc. restoring e- equilibrium. Best done in **dry air**
3. moist air L water coats everything and static charge cannot be maintained
4. **ANY** conducting object can be induced! Region of object nearest charged body will acquire a charge of opposite sign and region farthest from the charged body will acquire a charge of the same sign.





5. Charge transferred by conduction--when leaves <u>stay</u> diverged (acquired charge)--any conducting object acquires a residual charge of the same sign as that of the body touching it.

G. Residual charge by Induction
1. A charged rubber rod (-) is held near knob L no transfer of e-. When an isolated conductor is given a residual charge by induction, the charge is opposite in sign to that of the object inducing it.

H. The Force Between Charges

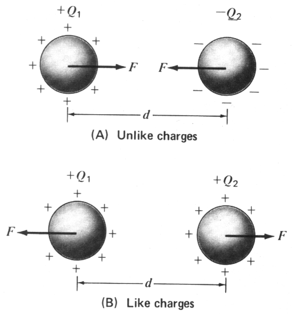


Figure 16-10. When Q_1 and Q_2 are of opposite sign, F is negative and is interpreted as a force of attraction. When Q_1 and Q_2 are of the same sign, F is positive and is interpreted as a force of repulsion.

1. point charges--when a uniform charge on the surface of a sphere causes the sphere to behave as if the charge were concentrated in the middle
2. q--quantity of charge & measured in coulombs (c); 1c = 6.25 x 10^{18} electrons 1 :c = 10^{-6} c q for an electron = -1.60 x 10^{-19} c q for a proton = +1.60 x 10^{-19} c
3. **COULOMB'S LAW** of electrostatics--*The force between 2 point charges is directly % to the product of their magnitudes and inversely % to the square of the distance between them.*

Coulomb's Law: $F = k\frac{qq'}{d^2}$ $F = \frac{1}{4B,_o}\frac{qq'}{d^2}$

a. K accounts for properties of medium separating charged bodies
b. K = 9.0 x 10^9 NCm^2/C^2 in a vacuum
c. $,_o$ = 1/4Bk = 8.85 x 10^{-12} C^2/NCm^2 called the **permitivity of free space**

d. - means repulsion + means attraction

II. ELECTRIC FIELDS--exist in a region of space if an electric charge placed in that region is subject to an elec. force.

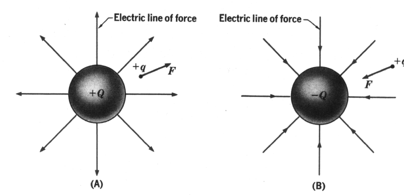
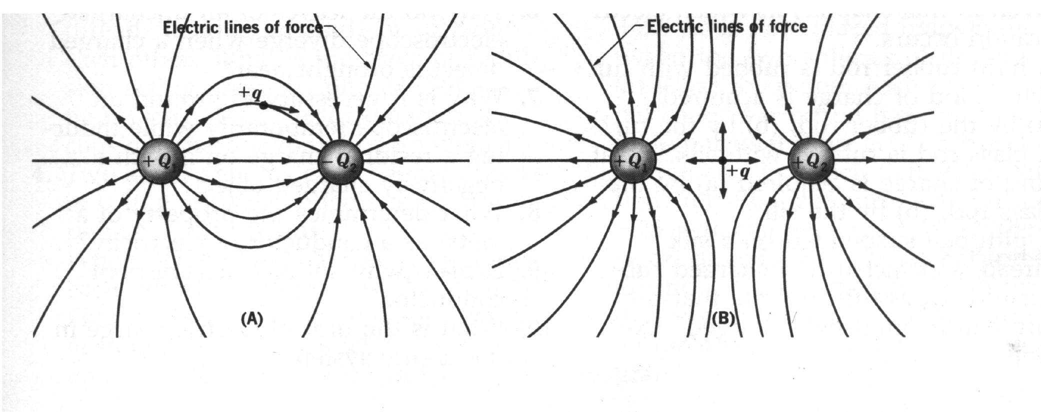


Figure 16-11. The electric field surrounding a charged sphere isolated in space.

A. Electric line of force--line so drawn that a tan to it at any point indicates the orientation of the electric field at that point.
   1. originate at surface of + charged body and terminate at surface of - charged body. Each line shows direction a + test charge would follow and is normal to the surface of



the charged body where it joins that surface.

2. Intensity--% to the # of lines of force per unit area normal to the field:

$$E = \frac{F}{q} = k\frac{Q}{r^2}$$

E L Electric field intensity
F L Force in Newtons
q L **POSITIVE** test charge in coulombs

EXAMPLE 1

Find the force between charges of +100.0 :c and -50.0 :c located 50.0 cm apart.

EXAMPLE 2

What force acts on two electrostatic charges of 60.8 :c and 76.5 :c isolated in air 42.5 cm apart?

EXAMPLE 3

Two small isolated spheres are 20.0 cm apart. The sphere on the left receives a charge of +10.8 ∶c and the sphere on the right receives a charge of +12.2 ∶c. What force acts on each charge and in what direction?

EXAMPLE 4 (vector flashback)

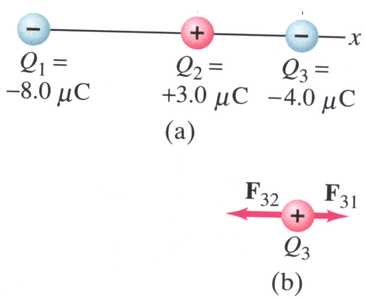


FIGURE 16–18 Diagram for Example 16–3.

Three charged particles are arranged in a line. Calculate the net electrostatic force on particle 3 due to the other 2 charges.

EXAMPLE 5

Calculate the net electrostatic force on charge Q_3 due to the other charges present.

EXAMPLE 6

Calculate the magnitude and direction of the electric field at a point P which is 30 cm to the right of a point charge Q = -3.0×10^{-6}

EXAMPLE 7

Two point charges are separated by a distance of 10.0 cm. One has a charge of - 25 :c and the other +50 :c.

a) What is the direction and magnitude of the electric field at point P in between them that is 2.0 cm from the negative charge?

b) If an electron is placed at rest at P, what will its acceleration be initially?

EXAMPLE 8

Calculate the total electric field at a point A and point B due to both charges Q_1 and Q_2

III. POTENTIAL DIFFERENCE

A. Electric Potential

1. A charge in an electric field experiences a force according to Coulomb's law

   a. If charge moves in response to force, work is done **by** elec. field and Energy is removed from the system

   b. If charge is moved against the coulomb force, work is done **on** it using Energy from some outside source, Energy is stored

   c. If work is done as a charge moves from 1 point to another in an electric field, or if work is required to move a charge from 1 point to another, these 2 points <u>differ in electric potential</u>.

   d. Magnitude of the work is a measure of this difference of potential

2. Potential difference, V, between 2 points in an electric field is the work done per unit charge as a charge is moved between these points:

$$V = \frac{\text{work}}{\text{charge}} = \frac{w}{q} = \frac{PE}{q}$$

   a. **<u>volt</u>**--V between 2 points in an electric field such that 1 joule of work is done in moving a charge of 1 coulomb between these points:

$$1 \text{ volt} = \frac{1 \text{ joule}}{1 \text{ coulomb}}$$

   b. Say, v = 6.0 and q = 3 x 10^2 μc V = w/q so
   W = Vq = 6.0 v x 300 μc x 1c/10^6 μc = .0018j
   Since j = 1 N·m it follows:

$$v = \frac{j}{c} = \frac{N \cdot m}{c}$$

$$\frac{v}{m} = \frac{N}{c} \text{ so}$$

$$E = \frac{N}{c} = \frac{v}{m}$$

   c. E is often expressed in v/m and is called the <u>potential gradient</u> --Δ in potential/unit distance

   d. Earth is a source and a sink for e-'s. E = 0 for Earth. Any conductor connected to Earth has an E = 0 and **is grounded**.

B. Distribution of Charges on an isolated object--Michael Faraday

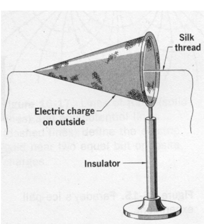
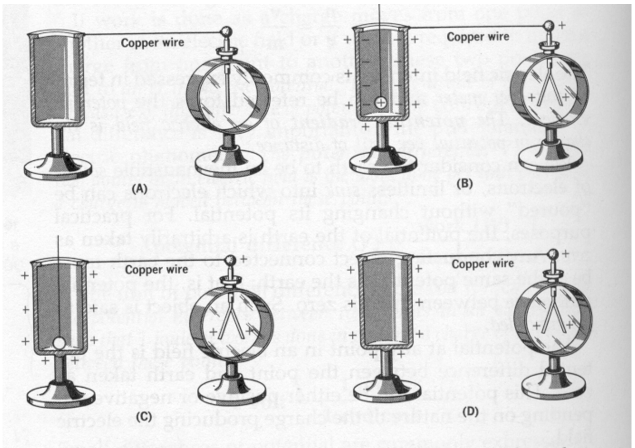


Figure 16-14. The type of conical silk bag used by Faraday to demonstrate that electric charges reside on the outside.

He charged a conical silk bag and found that the charge was on the outside of the bag.

Pull on the silk thread and turn the bag inside out and the charge was again on the outside of the bag.

Either way charge is on the **outside** of the silk bag.



1. **NO** redistribution of + charge on outside surface of pail
2. outside of pail acquired a net charge = to charge originally placed on the ball
3. *Conclude*:
    a. all static charge on a conductor lies on its surface
    b. there can be no V between 2 points on the surface of a charged conductor
    c. The surface of a conductor is an equipotential surface
    d. electric lines of force are normal to equipotential surface
    e. lines of force originate or terminate normal to the conductive surface of a charged object

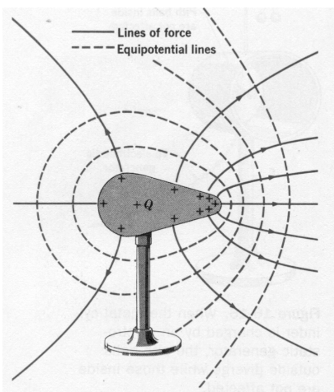


Figure 16-18. The charge density is greatest at the point of greatest curvature.

C. Effect of the shape of a conductor
1. Sphere has a uniform charge density (charge/area)
2. Charge acquired by nonconductor is confined to its original region until it gradually leaks away. Charge acquired by a conductor distributes itself according to the surface curvature, concentrating around points.

D. Discharging Effect of Points
1. If field is strong enough it can ionize gas molecules in air; + ion and e- respond to electric force. When air is ionized, point of conductor is rapidly discharged
2. Always some ions present and collisions produce more Y air is ionized rapidly
3. In dry air, E = 30 kv/cm between 2 charged surfaces to get air to ionize and a spark discharge occurs. Rush of free e- and ionized molecules discharging surfaces and producing heat, light and sound. Usually quantity of static elec. is small and time duration of spark discharge <u>very short</u>--lightening Y quantity of charge is great!!
4. Intensity of elec. field at corners is strong enough to ionize air Y violet glow. Brush/corona discharge Y St. Elmo's fire, tips of ship masts and trailing edges of wing and tail surfaces of aircraft.
5. Lightening--Rush of charges to meet opposites: cloud-cloud or cloud-Earth

E. Electric potential, V, is a scalar and electric field, E, is a vector
1. If we move a + charge between two parallel charged plates whose potential differs by V, the Work done by the electric field to move the charge is = qV AND W = Fd = qEd [which means F = qE]. Set them equal to each other and E = V/d or V = Ed.
2. The units of electric field are V/m or N/c.

Example 1

Suppose an electron in the picture tube of a television is accelerated from rest through a potential difference of +5,000 V

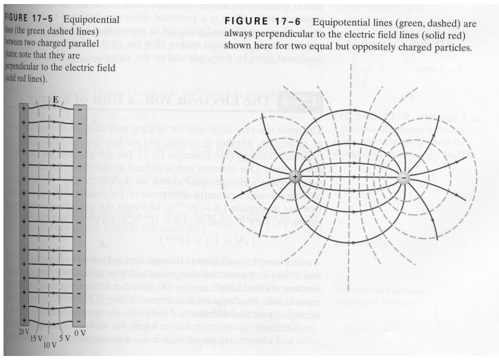
a) What is the change in PE of the electron?

b) What is the speed of the electron ($m = 9.1 \times 10^{-31}$kg) as a result of this acceleration?

c) Repeat for a proton ($m = 1.67 \times 10^{-27}$kg) that accelerates through a potential difference of - 5,000 V.

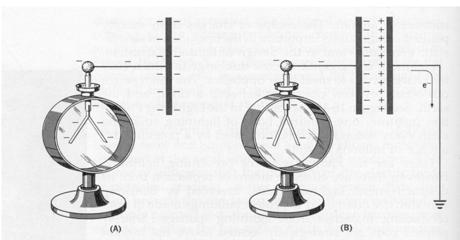
Example 2

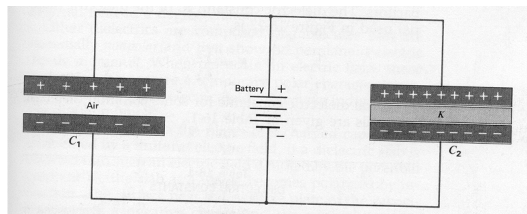
Two parallel plates are charged to a voltage of 50 V. If the separation between the plates is 0.050 m, calculate the electric field between them



F. Capacitors--any isolated conductor can retain a charge. Can increase charge until spark--in a vacuum, can withstand more charge

1. a combination of conduction plates separated by an insulator that is used to store an electric charge is known as a capacitor
    a. area of plates
    b. distance of separation
    c. char. of insulating material determine charge that can be placed on capacitor





2. Larger charge--greater is E between plates
    a. Ratio of q:V is a constant for a given capacitor--Capacitance,C C = ratio of q:V $C = \frac{q}{V}$

    C is measured in farads, C = 1f when a charge of 1 c on a capacitor results in a V of 1v between plates

G. Dielectric Materials--Faraday

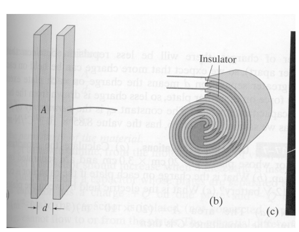
H. Effect of different insulating materials between plates of capacitors--using plates of equal area and spacing and comparing with air, C_2 had greater charge than $C_{1(air)}$ by a factor of K

$q_2 = Kq_1$ $\frac{q_2}{v} = K\frac{q_1}{v}$ thus $C_2 = KC_1$

1. Materials used to separate plates of capacitors are known as dielectrics. K, dielectric constant
    a. dry air K = 1.0006 (unity w/ vacuum)
    b. dimensionless
    c. $K = \frac{C_2}{C_1}$

TABLE 17–3
Dielectric Constants (20°C)

Material	Dielectric Constant, K
Vacuum	1.0000
Air (1 atm)	1.0006
Paraffin	2.2
Rubber, hard	2.8
Vinyl (plastic)	2.8–4.5
Paper	3–7
Quartz	4.3
Glass	4–7
Porcelain	6–8
Mica	7
Ethyl alcohol	24
Water	80



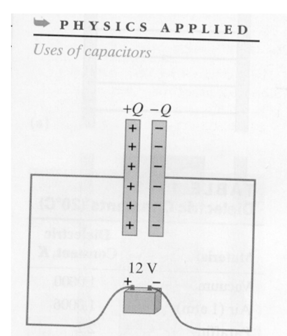


FIGURE 17–13 Parallel-plate capacitor connected to a battery.

Molecular description of dielectrics

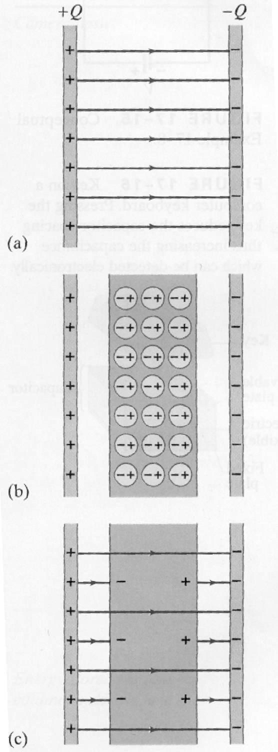


FIGURE 17–14 Molecular view of the effects of a dielectric.

I. The effect of dielectrics

1. <u>electric dipole moment</u>--permanent separation of charge polar or dipole molecules. (Align in an electric field)
2. Other dielectrics are nonpolar--can achieve temporary polar characteristics by induction
   - a. dielec. slab inserted--slab polarized by induction--surfaces become charged--result from dipole moments of dielectric molecules NOT from transfer of e-.
   - b. Elec. field in slab by surface charge opposes the external field---E = vector sum

TABLE 17–2 Dipole Moments of Selected Molecules

Molecule	Dipole Moment (C·m)
$H_2^{(+)}O^{(-)}$	6.1×10^{-30}
$H^{(+)}Cl^{(-)}$	3.4×10^{-30}
$N^{(-)}H_3^{(+)}$	5.0×10^{-30}
$>N^{(-)}—H^{(+)‡}$	$\approx 3.0 \times 10^{-30}$
$>C^{(+)}=O^{(-)‡}$	$\approx 8.0 \times 10^{-30}$

‡These groups often appear on larger molecules; hence the value for the dipole moment will vary somewhat, depending on the rest of the molecule.

3. Large capacitances achieved by large plate areas; insulators with high K; small separation of plates.
   - a. dielectric strength limits the reduction in spacing between plates and defines quality of the material as an insulator
   - b. Potential gradient will withstand being punctured by a spark discharge

Example 7

a) Calculate the capacitance of a capacitor whose plates are 20 cm x 3.0 cm and are separatedby a 1.0 mm air gap.

b) What is the charge on each plate if the capacitor is connected to a 12-V battery?

c) What is the electric field between the plates?

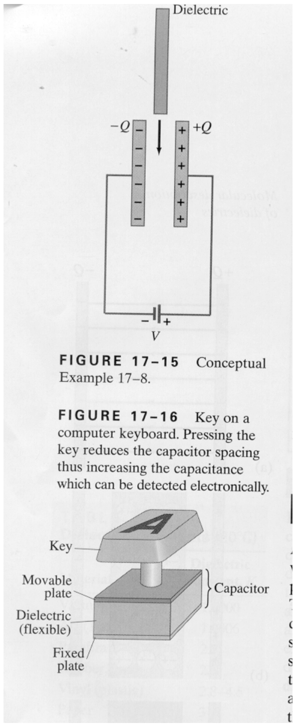


FIGURE 17–15 Conceptual Example 17–8.

FIGURE 17–16 Key on a computer keyboard. Pressing the key reduces the capacitor spacing thus increasing the capacitance which can be detected electronically.

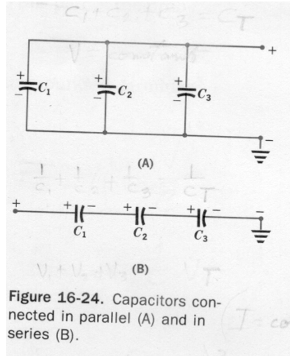


Figure 16-24. Capacitors connected in parallel (A) and in series (B).

J. Combinations of Capacitors

1. C_1, C_2, C_3 in parallel--1 plate to 1 conductor while another plate connected to a second conductor ˆ same V across all

$q_1 = C_1 v$, $q_2 = C_2 v$, $q_3 = C_3 v$

$q_T = q_1 + q_2 + q_3$

$q_T = C_1 v + C_2 v + C_3 v$

$q_T = C_T v$

sub $C_T v = C_1 v + C_2 v + C_3 v$

$C_T = C_1 + C_2 + C_3$

2. C_1, C_2, C_3 in series

$q = q_1 = q_2 = q_3$ since charge is transferred

$v_T = v_1 + v_2 + v_3$ AND $v_T = \frac{q}{C_T}$ AND $V_1 = \frac{Q}{C_1}$

$$C_T = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$

SUMMARY:

$E = \frac{F}{q}$

E L Electric field intensity

F L Force in Newtons

q L test charge in coulombs

$C = \frac{q}{V}$

$K = \frac{C_2}{C_1}$

Potential Difference, $V = \frac{\text{work}}{\text{charge}} = \frac{w}{q} = \frac{PE}{q} = Ed$

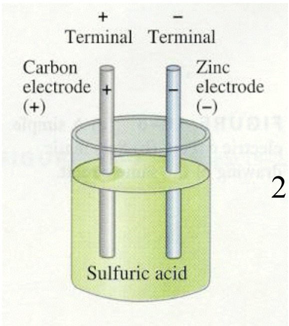
$1 \text{ volt} = \frac{1 \text{ joule}}{1 \text{ coulomb}}$

Capacitors in parallel: $C_T = C_1 + C_2 + C_3$

Capacitors in series: $C_T = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$

IV. Electric Currents

A. Volta vs. Galvani–1800ish. Before these guys, all we knew about electricity involved static charges. Even Ben Franklin and his kite.

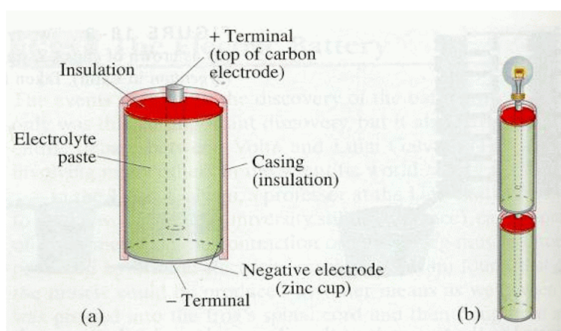


1. Galvani was a professor in Italy and conducted a series of experiments involving a [dead] frog's leg and making it jump using static electricity. One of these involved a brass hook that was pressed into a frog's spine and hung from an iron railing that also touched the frog. Galvani called it "animal electricity" and published his work in 1791. Many thought he had found the still elusive "life force".

2. Volta was skeptical–he thought the source of the electricity had nothing to do with the animal but rather the 2 metals in contact. He did some experiments of his own and discovered that moisture [formerly provided by recently deceased frog] was required as a conductor. His greatest contribution was the "battery".

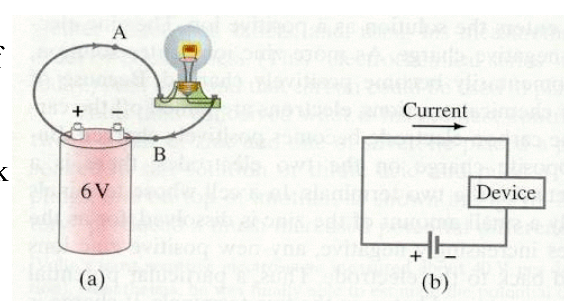
3. We still refer to the type of battery he constructed as a Voltaic or Galvanic cell. It consists of 2 dissimilar metals as electrodes [carbon or platinum can serve as an "inert" electrode in place of one of the metals] immersed in an electrolyte [dilute solution of a strong acid or a nitrate solution of the metal serving as the electrode in that cell] and a connecting wire. This picture shows the electrodes together in one container, it's more efficient to use 2 containers and a salt bridge to connect the two containers as well as wires to connect the two electrodes. The battery goes "dead" when chemical equilibrium is reached.

4. If you connect the + terminal of one battery to the - terminal of the next they are connected in **series**. If you link + to + and - to-, then they are in **parallel**.



B. Electric Current–no longer static–electrons in motion!

1. When we have a continuous conducting path between the terminals of a battery, we have an electric current. Notice the longer line of the battery notation on the schematic is + while the shorter line is negative. [it takes more ink to write a + than a neg. sign and this works the same way, it takes more ink to write the longer line, therefore it must be +]



2. Note the current flows from + to -.

3. **<u>Electric current</u>**–the net amount of charge that passes through it per unit time at any point. $I = \Delta Q/\Delta t$ It's unit is the ampere, amp, A = 1 C/second

4. In any single circuit, the current at any instant is the same at one point as at any other point since electric charge is conserved.

Example 1

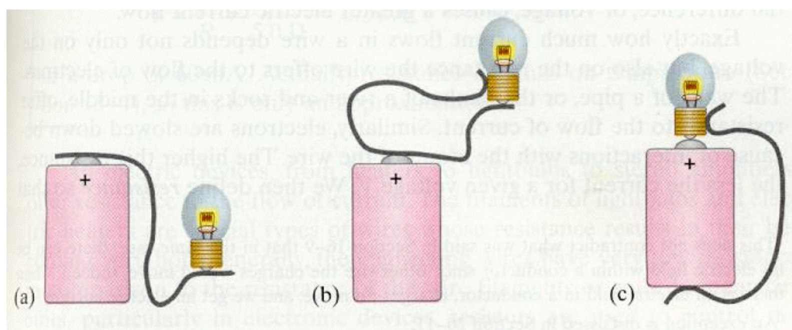
A steady current of 2.5 A flows in a wire for 4.0 minutes.

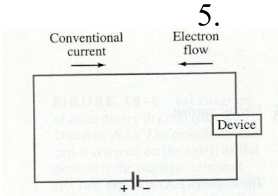
a) How much charge passed through any point in the circuit?

b) How many electrons would this be?

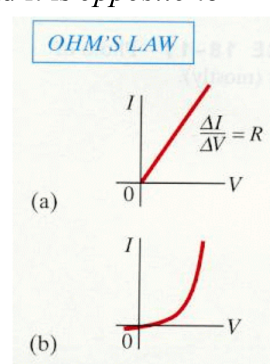
Example 2

What's wrong with this picture?





5. Conventional current. It would be a while before anyone knew about electrons. When the rules of this game were being set, everyone assumed positive charge flowed in a circuit. Be clear in your language–conventional current traces the path of positive charge. Electron current tracks the path of the electron flow and it is *opposite* to conventional current.



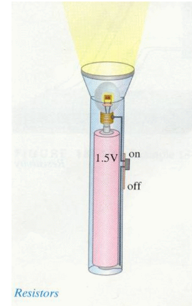
C. Ohm's Law: Resistance and Resistors

1. To produce an electric current in a circuit, a difference in potential is required. Georg Simon Ohm (17877-1854) determined $I \propto V$

2. This is also affected by resistance of a wire or other device to the flow of current and it varies inversely with current so $I = V/R$ Some physicists take issue with "law". R is measured in ohms, Ω

Ohm's Law: $V = IR$

Example 3
A small flashlight bulb draws 300 mA from its 1.5 volt battery.
a) What is the resistance of the bulb?



b) If the voltage dropped to 1.2 volt, how would the current change?

All electric devices offer resistance to the flow of current. Filaments in light bulbs and the heating coils of electric heaters and stoves result in their becoming HOT.

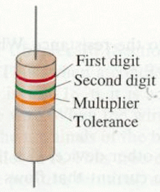


FIGURE 18–12 The resistance value of a given resistor is written on the exterior, or may be given as a color code, as shown above and in the table: the first two colors represent the first two digits in the value of the resistance, the third color represents the power of ten that it must be multiplied by, and the fourth is the manufactured tolerance. For example, a resistor whose four colors are red, green, orange, and silver has a resistance of 25,000 Ω (25 kΩ), give or take 10 percent.

Resistor Color Code

Color	Number	Multiplier	Tolerance (%)
Black	0	1	
Brown	1	10^1	
Red	2	10^2	
Orange	3	10^3	
Yellow	4	10^4	
Green	5	10^5	
Blue	6	10^6	
Violet	7	10^7	
Gray	8	10^8	
White	9	10^9	
Gold		10^{-1}	5%
Silver		10^{-2}	10%
No color			20%

TABLE 18–1 Resistivity and Temperature Coefficients (at 20°C)

Material	Resistivity, ρ ($\Omega \cdot m$)	Temperature Coefficient, α $(C°)^{-1}$
Conductors		
Silver	1.59×10^{-8}	0.0061
Copper	1.68×10^{-8}	0.0068
Gold	2.44×10^{-8}	0.0034
Aluminum	2.65×10^{-8}	0.00429
Tungsten	5.6×10^{-8}	0.0045
Iron	9.71×10^{-8}	0.00651
Platinum	10.6×10^{-8}	0.003927
Mercury	98×10^{-8}	0.0009
Nichrome (alloy of Ni, Fe, Cr)	100×10^{-8}	0.0004
Semiconductors[†]		
Carbon (graphite)	$(3–60) \times 10^{-5}$	−0.0005
Germanium	$(1–500) \times 10^{-3}$	−0.05
Silicon	0.1 − 60	−0.07
Insulators		
Glass	$10^9 - 10^{12}$	
Hard rubber	$10^{13} - 10^{15}$	

[†]Values depend strongly on presence of even slight amounts of impurities.

3. Resistors can be used to control the amount of current. The range of resistors is less than 1 ohm to millions of ohms. Wire-wound resistors consist of a coil of fine wire and composition resistors are usually made of the semiconductor carbon.
4. **Resistivity**–The R of a metal wire is direcly % to its length, L, and inversely proportional to the corss-sectional area, A. Where rho is a resistivity and depends on the material used.

$$R=\rho\frac{L}{A}$$

Example 4

Suppose you want to connect your stereo to remote speakers.

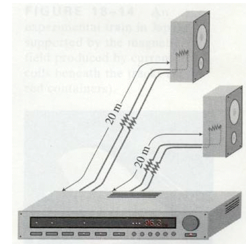


FIGURE 18–13 Example 18–4.

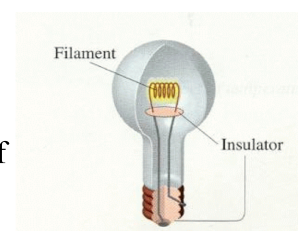
a) If each wire must be 20 m long, what diameter copper wire should you use to keep the resistance less than 0.10 S per wire?

b) If the current to each speaker is 4.0 A, what is the voltage drop across each wire?

Example 5

A wire of resistance R is stretched uniformly until it is twice its original length. What happens to its resistance? Justify.

D. Electric Power



1. Electric heaters, stoves, toasters and hair dryers convert electrical energy into thermal energy. In a lightbulb the tiny wire filament becomes so hot it glows. Only a few percent of the energy is transformed into visible light, 90% is converted into thermal energy.
2. Collisions between the electrons and the atoms of the metal conductor cause the heat to be produced. The KE of the electron is transferred to the metal's atom and increases its KE which raises the temperature.
3. $P = \text{power} = \dfrac{\text{energy transformed}}{\text{Time}} = \dfrac{QV}{t}$
4. The charge that flows per unit second, Q/t is simply the electric current, I so...

$$P = IV = I^2R = V^2/R$$

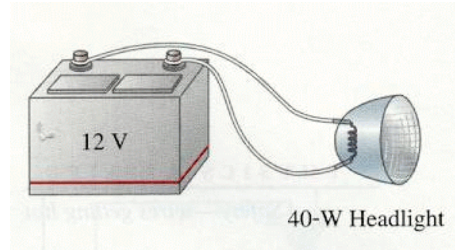
Use V = IR to generate the other forms:

P = IV = I (IR)

= (V/R)V

Example 7

Calculate the resistance of a 40 watt automobile headlight designed for 12 V.



Example 8

An electric heater draws 15.0 A on a 120-V line. How much power does it use and how much does it cost per month (30 days) if it operates 3.0 h per day and the electric company charges 10.5 cents per kWh?

Example 9

Lightning is a spectacular example of electric current in a natural phenomenon. There is much variability to lightning bolts, but a typical event can transfer 10^9 J of energy across a potential difference of perhaps 5×10^7 V during a time interval of about 0.2 s. Use this information to estimate the total amount of charge transferred, the current and the average power over the 0.2 s.

V. DC CIRCUITS

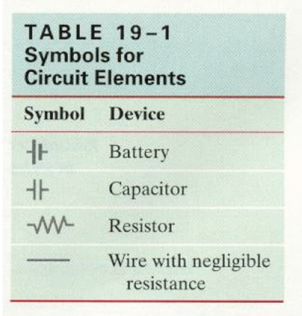


TABLE 19–1 Symbols for Circuit Elements

Symbol	Device
⊣⊢	Battery
⊣⊢	Capacitor
-WW-	Resistor
——	Wire with negligible resistance

A. Circuit diagrams–A short-hand way of depicting the components in a direct current [battery] circuit.

B. <u>Resistors in Series</u>–2 or more resistors are connected end to end. Resistors could be simple resistors [the striped things] or light bulbs, heating elements, or other resistive devices.

1. I is equal across all resistors in a series
2. $V = V_1 + V_2 + V_3 = IR_1 + IR_2 + IR_3$ My students came up with a clever way to remember this. They had "Sr. V" as in

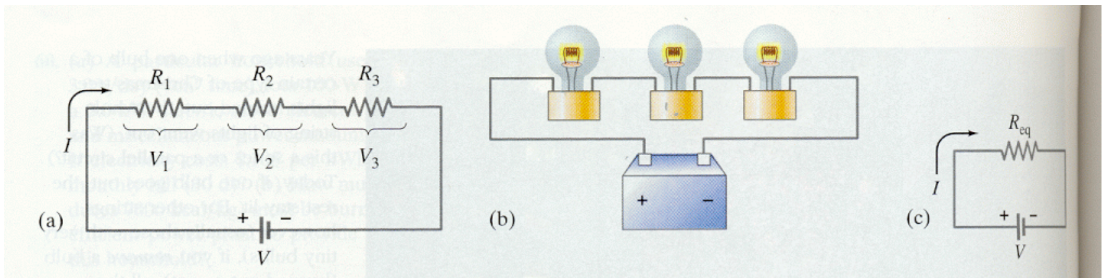
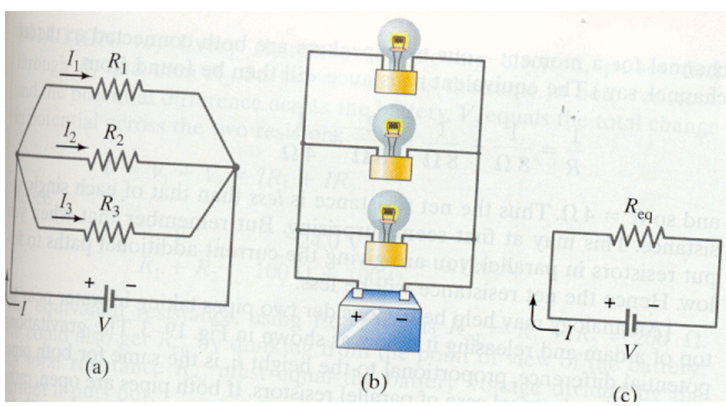


FIGURE 19–1 (a) Resistances connected in series: $R_{eq} = R_1 + R_2 + R_3$. (b) Resistances could be lightbulbs, or any other type of resistance. (c) Equivalent single resistance R_{eq} that draws the same current.

seniors are victorious. It helped them remember that in **<u>S</u>**ERIES, **<u>R</u>**esistors & **<u>V</u>**oltage are additive. {They already knew that capacitor behave "opposite" to resistors.}

3. <u>Equivalent Resistor</u>–Since resistors are additive in series, you can replace all those zig-zag's with one equivalent [the sum of] zig zag like the picture above on the far right. The relationship is $V = I R_{eq}$. This simplifies things!



C. <u>Resistors in parallel–</u> Here the current from the source *splits* into two or more branches. This is how the wiring in buildings and houses is done. This way, if you disconnect one device, the current to the others is not disrupted. With series, if one goes out, the current is stopped!

1. I is split across the branches and is therefore additive

$I = I_1 + I_2 + I_3$ WHERE EACH I = V/it's R AND total $I = V/R_{eq}$

2. It follows that $\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$ This means that the NET resistance in parallel is LESS than any single resistor since you are giving the current additional paths to follow, hence the resistance will be less.

3. Here's an analogy: Consider 2 pipes taking in water near the top of a dam and releasing it below as shown here. The gravitational potential difference, % h, is the same for both pipes, just as in the electrical case of parallel resistors. If both pipes are open, rather than only one, twice as much current will flow through. This, with 2 equal pipes open, the net resistance to the flow of water will be reduced by half.

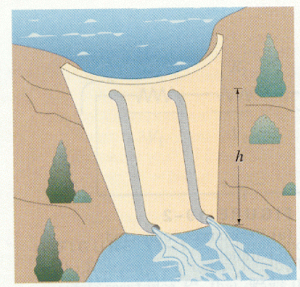


FIGURE 19–3 Water pipes in parallel—analogy to electric currents in parallel.

Example 1

a) The light bulbs in this figure are identical and have identical resistance R. Which configuration produces more light?

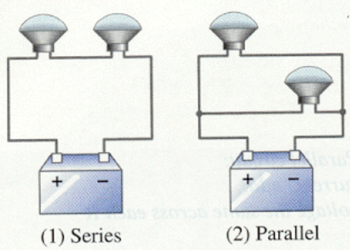
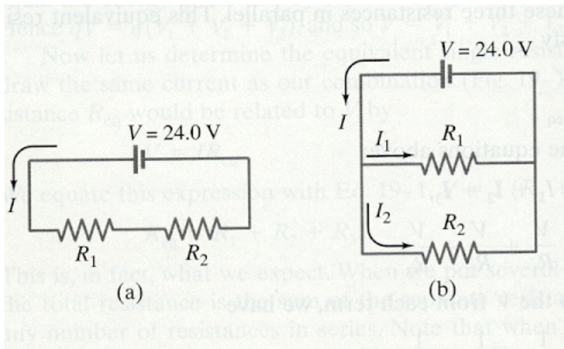


FIGURE 19–4 Example 19–1.

b) Which way do you think the headlights of a car are wired?

Example 2
Two 100-S resistors are connected (a) in series and (b) in parallel, to a 24.0 V battery. What is the current through each resistor and what is the equivalent resistance of each circuit?



Note that whenever a group of resistors is replaced by R_{eq}, I and V and P in the rest of the circuit are unaffected.

Example 3
How much current flows from the battery in this diagram?

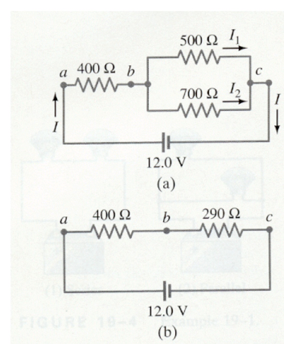


FIGURE 19–6 (a) Circuit for Examples 19–3 and 19–4. (b) Equivalent circuit, showing the equivalent resistance of 290 Ω for the two parallel resistors in (a).

Example 4

What is the current flowing through the 500 S resistor?

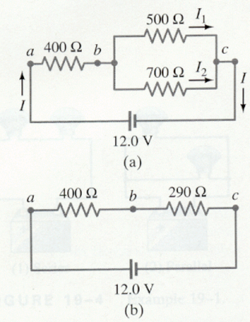


FIGURE 19–6 (a) Circuit for Examples 19–3 and 19–4. (b) Equivalent circuit, showing the equivalent resistance of 290 Ω for the two parallel resistors in (a).

Example 5

The circuit shown has three identical light bulbs, each of resistance R.

a) When switch S is closed, how will the brightness of bulbs A & B compare with that of bulb C?

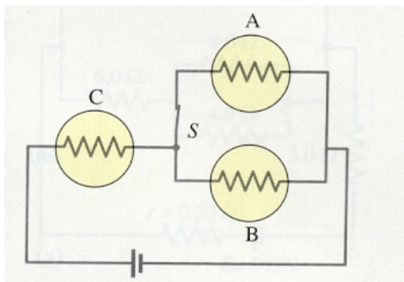
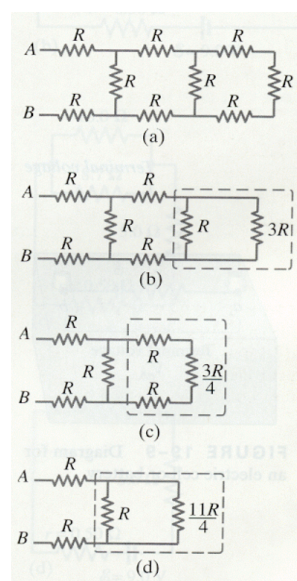


FIGURE 19–7 Example 19–5, three identical lightbulbs.

b) What happens when switch S is opened? Use a minimum of mathematics in your answers.

Example 6

Estimate the equivalent resistance of the "ladder" of equal 100 S resistors shown. In other words, what would an ohmmeter read if connected between points A and B?



D. **EMF and Terminal Voltage**–A device such as a battery or an electric generator that transforms one type of energy (chem., mech, light, etc.) into electrical energy is called a seat or source of electromotive force or emf or õ . The potential difference between the terminals of such a source, when no current flows to an external circuit is called the emf of the source. So, you see, it's not a force measured in Newtons–it's measured in VOLTS since it's a measure of potential difference.

1. Ever notice that if you turn the headlights on in your car BEFORE starting it, that the headlight's dim during the start process? That's due to the fact that the lead storage battery's electron's flow isn't fast enough to supply the charge you demand instantaneously. Every battery has **internal resistance** symbolized by r.
2. **Terminal voltage**–when there is no current drawn from the battery, V_{ab} = õ. Once you start to draw a current, I, the internal resistance of the battery kicks in and the actual voltage delivered is what we call the terminal voltage and is calculated

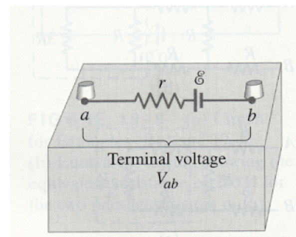


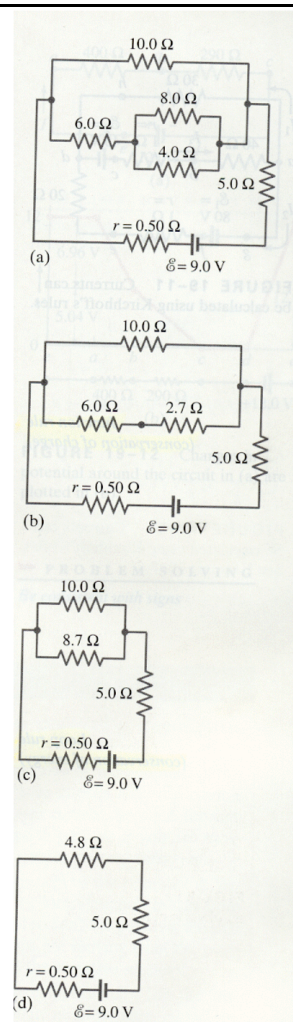
FIGURE 19–9 Diagram for an electric cell or battery.

V_{ab} = õ - Ir

Example 7

A 9.0 V battery whose infernal resistance, r, is 0.50 S is connected in the circuit shown.

a) How much current is drawn from the battery?



b) What is the terminal voltage of the battery?

c) What is the current in the 6.0 S resistor?

VI. Kirchhoff's Rules

A. These rules were invented in the mid 1800's to deal with complicated circuits. There are 2 rules and they are simply convenient applications of the laws of conservation of charge and energy.

B. Kirchhoff's first rule–the junction rule, based on the conservation of charge which we already used in deriving the rule for parallel resistors.

At any junction point, the sum of all currents entering the junction must equal the sum of all currents leaving the junction.

"What goes in must come out!" Charges entering a junction must also leave–none is lost or gained.

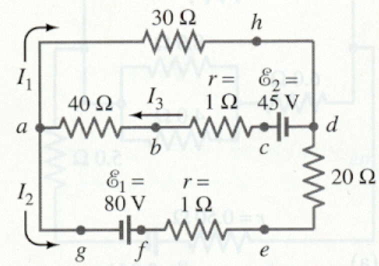


FIGURE 19–11 Currents can be calculated using Kirchhoff's rules.

C. Kirchhoff's second rule–the loop rule, based on the conservation of energy.

The sum of the changes in potential around any closed path of a circuit must be zero.

D. Examine the junction at point a. I_3 is entering whereas I_1 and I_2 are leaving. The junction rule states that $I_3 = I_1 + I_2$

E. Examine this circuit [you'll get your chance with the above circuit in our next example problem].

1. I = 12.0 V / 690 S = .0174 A
2. The + side e has more potential than d
3. Follow a + test charge from point e, point d is taken as zero. When we return to e, the potential there will be the same as when we started.
4. From e ÷ a, no change since no source of V or R.
5. From a ÷ b, there is a voltage drop of V= IR = 0.0174 A x 400 S = 6.96 V [the + charge is flowing "downhill" toward the negative terminal]. Use a negative sign to show the drop in V.
   $V_{ba} = V_a - V_b = -6.96$ V
6. From b ÷ c, further voltage drop V = IR = 0.0714 A x 290 S = 5.04 S which we give a negative sign since it is a drop in voltage.
7. From c ÷ d, there is no change in voltage.
8. From d ÷ a, there is a POSITIVE 12.0 Voltage increase.
9. Therefore the sum of all the changes in potential is
   -6.96 V - 5.04 V + 12.0V = 0 Thus, the loop rule is satisfied.

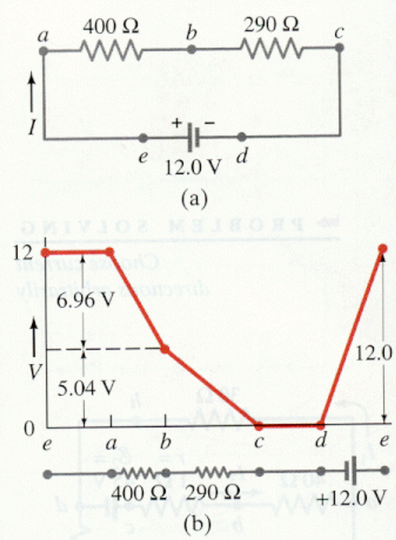


FIGURE 19–12 Changes in potential around the circuit in (a) are plotted in (b).

Example 8

Calculate the currents I_1 , I_2, and I_3 in each of the branches of this circuit.

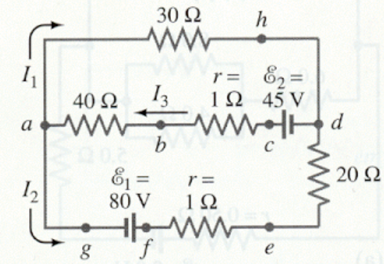


FIGURE 19–11 Currents can be calculated using Kirchhoff's rules.

F. EMFs in Series and in Parallel; Charges in a Battery

1. <u>Series arrangement</u>–Remember "Sr. V", in series V's and R's are additive so the voltage is the sum of the series EMFs.
2. Figure b has the batteries attached OPPOSITELY so subtract 20V-12V = 8V. Follow the positive test charge from a to c. Seems wasteful? This is how alternators in cars and battery chargers work. It forces electrons to the negative terminal removing them from the positive.
3. Figure c shows parallel–used when provide more I such as starting a diesel engine. V's are equal in parallel so each cell has to produce only a fraction of the total current, so the loss due to internal resistance

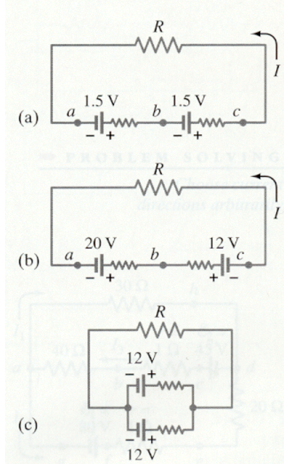


FIGURE 19–14 Batteries in series, (a) and (b), and in parallel, (c).

is less than for a single cell; batteries go dead less quickly.

G. Circuits containing Capacitors in Series and in Parallel

1. In series R's are additive. In parallel R's are reciprocal and additive

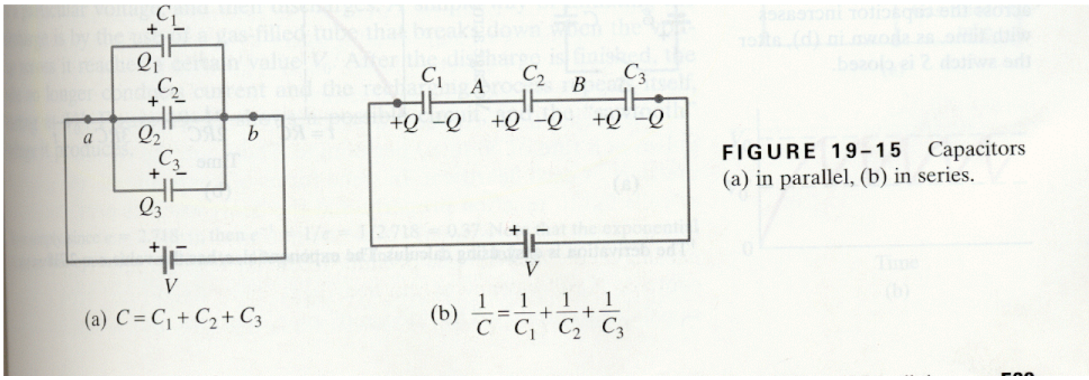


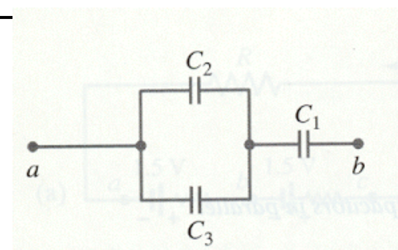
FIGURE 19–15 Capacitors (a) in parallel, (b) in series.

2. In series C's are reciprocal and additive. In parallel, C's are additive.

3. $Q_1 = CV_1$ and $Q_2 = CV_2$ etc.. The total charge that must leave the battery is $Q = Q_1 + Q_2 ...$, so $Q = C_{eq}V$ What is really happening by adding capacitors in series is that we are increasing the effective area of the plates so that total or equivalent capacitance increases.

Example 9

Determine the capacitance of a single capacitor that will have the same effect and the combination shown here. Take $C_1 = C_2 = C_3 = C$



H. <u>RC Circuits</u>–those containing both a resistor and a capacitor.

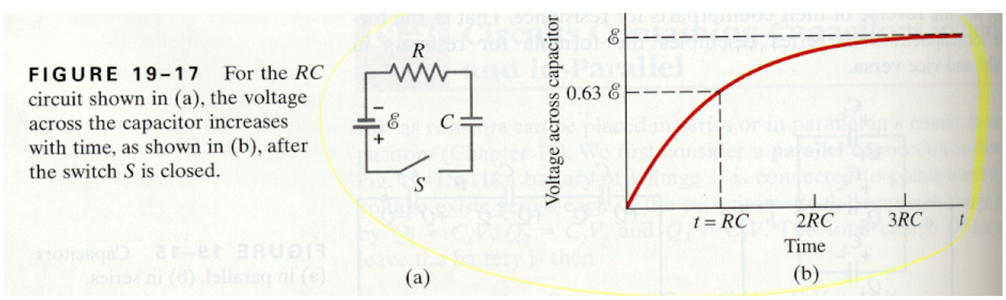


FIGURE 19–17 For the RC circuit shown in (a), the voltage across the capacitor increases with time, as shown in (b), after the switch S is closed.

1. Close the switch S. Electrons will flow out of the negative terminal and accumulate [a negative charge] on the upper place of the capacitor. AND electrons will flow into the + terminal of the battery leaving a + charge on the other [lower] plate of the capacitor.

2. As charge accumulates on the capacitor, the potential difference, V, across it increases and the current is reduced until eventually the V across the capacitor equals the emf of the battery, õ. Now there is no potential difference across the R and no further current flow!

3. The potential difference across the capacitor, which is proportional to the charge on the capacitor [V = Q/C] thus increases in time. Note this is an exponential curve.
4. What if we discharge the charged capacitor? No battery needed for this:

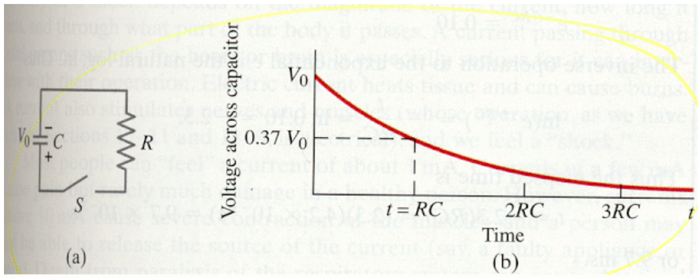


FIGURE 19–18 For the *RC* circuit shown in (a), the voltage *V* on the capacitor decreases with time, as shown in (b), after the switch *S* is closed. The charge on the capacitor follows the same curve since $Q \propto V$.

5. When the switch is closed, charge begins to flow through resistor R from one side of the capacitor toward the other side, until it is fully discharged. Note this curve follows one of exponential decay.

Summary:

"Sr. V"–nemonic to help you remember what's additive and what's equal in series vs. parallel circuits. Resistors are "opposite" to capacitors and are the only components that have the "reciprocal and additive" thing going on! V's and I's are either additive or equal

Sr. V means in Series, **R** 's & **V** 's are additive, so that means that C's must be additive and reciprocal while I's must be equal.

Turn all of that around and that means that for parallel, R is reciprocal and additive while C is just additive and V's are equal while I must be additive.

Series [think Sr.V]	**Parallel**
$R_{eq} = R_1 + R_2 + R_3$...	$1/R_{eq} = 1/R_1 + 1/R_2 \; +1/R_3$ ...
$1/C_{eq} = 1/C_1 + 1/C_2 \; +1/C_3$ ...	$C_{eq} = C_1 + C_2 + C_3$...
$V_T = V_1 + V_2 + V_3$...	$V_T = V_1 = V_2 = V_3$...
$I_T = I_1 = I_2 = I_3$...	$I_T = I_1 + I_2 + I_3$...